

On the phenomenology of a two-Higgs-doublet model with maximal CP symmetry at the LHC – synopsis and addendum

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Predictions for LHC physics are given for a two-Higgs-doublet model having four generalized CP symmetries. In this *maximally-CP-symmetric model* (MCPM) the first fermion family is, at tree level, uncoupled to the Higgs fields and thus massless. The second and third fermion families have a very symmetric coupling to the Higgs fields. But through the electroweak symmetry breaking a large mass hierarchy is generated between these fermion families. Thus, the fermion mass spectrum of the model presents a rough approximation to what is observed in Nature. In the MCPM the couplings of the Higgs bosons to the fermions are completely fixed. This allows us to present clear predictions for the production at the LHC and for the decays of the physical Higgs bosons. As salient feature we find rather large cross sections for Higgs-boson production via Drell–Yan type processes. In this paper we present a short outline of the model and extend a former study by the predictions at LHC for a center-of-mass energy of 7 TeV.

1. INTRODUCTION

Extending the Standard Model (SM) Higgs sector to two Higgs doublets,

$$\varphi_1 = \begin{pmatrix} \varphi_1^+ \\ \varphi_1^0 \end{pmatrix}, \quad \varphi_2 = \begin{pmatrix} \varphi_2^+ \\ \varphi_2^0 \end{pmatrix}, \quad (1)$$

gives the two-Higgs-doublet model (THDM). There, the potential may contain many more terms than in the SM; see e.g. [1, 2]. The most general THDM Higgs potential can be written [3]

$$\begin{aligned} V = & m_{11}^2(\varphi_1^\dagger \varphi_1) + m_{22}^2(\varphi_2^\dagger \varphi_2) - m_{12}^2(\varphi_1^\dagger \varphi_2) - (m_{12}^2)^*(\varphi_2^\dagger \varphi_1) + \frac{1}{2}\lambda_1(\varphi_1^\dagger \varphi_1)^2 + \frac{1}{2}\lambda_2(\varphi_2^\dagger \varphi_2)^2 + \lambda_3(\varphi_1^\dagger \varphi_1)(\varphi_2^\dagger \varphi_2) \\ & + \lambda_4(\varphi_1^\dagger \varphi_2)(\varphi_2^\dagger \varphi_1) + \frac{1}{2}[\lambda_5(\varphi_1^\dagger \varphi_2)^2 + \lambda_5^*(\varphi_2^\dagger \varphi_1)^2] + [\lambda_6(\varphi_1^\dagger \varphi_2) + \lambda_6^*(\varphi_2^\dagger \varphi_1)](\varphi_1^\dagger \varphi_1) + [\lambda_7(\varphi_1^\dagger \varphi_2) + \lambda_7^*(\varphi_2^\dagger \varphi_1)](\varphi_2^\dagger \varphi_2), \end{aligned} \quad (2)$$

with $m_{11}^2, m_{22}^2, \lambda_{1,2,3,4}$ real and $m_{12}^2, \lambda_{5,6,7}$ complex. Many properties of THDMs turn out to have a simple geometric meaning if we introduce gauge invariant bilinears [4, 5],

$$K_0 = \varphi_1^\dagger \varphi_1 + \varphi_2^\dagger \varphi_2, \quad \mathbf{K} = \begin{pmatrix} K_1 \\ K_2 \\ K_3 \end{pmatrix} = \begin{pmatrix} \varphi_1^\dagger \varphi_2 + \varphi_2^\dagger \varphi_1 \\ i\varphi_2^\dagger \varphi_1 - i\varphi_1^\dagger \varphi_2 \\ \varphi_1^\dagger \varphi_1 - \varphi_2^\dagger \varphi_2 \end{pmatrix}. \quad (3)$$

In terms of these bilinears K_0, \mathbf{K} , the Higgs potential (2) reads

$$V = \xi_0 K_0 + \boldsymbol{\xi}^T \mathbf{K} + \eta_{00} K_0^2 + 2K_0 \boldsymbol{\eta}^T \mathbf{K} + \mathbf{K}^T E \mathbf{K} \quad (4)$$

with parameters ξ_0, η_{00} , 3-component vectors $\boldsymbol{\xi}, \boldsymbol{\eta}$ and a 3×3 matrix $E = E^T$, all real.

The standard CP transformation of the Higgs-doublet fields is defined by

$$\varphi_i(x) \rightarrow \varphi_i^*(x'), \quad i = 1, 2 \quad x' = (x^0, -\mathbf{x}). \quad (5)$$

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In terms of the bilinears, this standard CP transformation is [6, 7]

$$K_0(x) \rightarrow K_0(x'), \quad \mathbf{K}(x) \rightarrow \bar{R}_2 \mathbf{K}(x') \quad (6)$$

where $\bar{R}_2 = \text{diag}(1, -1, 1)$, corresponding in K space to a reflection on the 1–3 plane. Generalised CP transformations (GCPs) are defined by [8–10]

$$\varphi_i(x) \rightarrow U_{ij} \varphi_j^*(x'), \quad i, j = 1, 2, \quad (7)$$

with U an arbitrary unitary 2×2 matrix. In terms of the bilinears this reads [7]

$$K_0(x) \rightarrow K_0(x'), \quad \mathbf{K}(x) \rightarrow \bar{R} \mathbf{K}(x') \quad (8)$$

with an improper rotation matrix \bar{R} .

Requiring $\bar{R}^2 = \mathbb{1}_3$ leads to two types of GCPs. In K space:

- (i) $\bar{R} = -\mathbb{1}_3$, point reflection,
- (ii) $\bar{R} = R^T \bar{R}_2 R$, reflection on a plane ($R \in SO(3)$).

While the CP transformations of type (ii) are equivalent to the standard CP transformation (5), respectively (6), the point reflection transformation of type (i) is quite different and turns out to have very interesting properties. Motivated by this geometric picture of generalised CP transformations, the most general THDM invariant under the point reflection (i) has been studied in [11–13]. The corresponding potential has to obey the conditions $\xi = \eta = 0$,

$$V_{\text{MCPM}} = \xi_0 K_0 + \eta_{00} K_0^2 + \mathbf{K}^T E \mathbf{K}. \quad (9)$$

This model is, besides the point reflection symmetry of type (i), invariant under three GCPs of type (ii). We call this model therefore maximally CP symmetric model, MCPM. Requiring also maximally CP symmetric Yukawa couplings we find that at least two fermion families are necessary in order to have non-vanishing fermion masses. That is, we find a reason for family replication in the MCPM. Furthermore, requiring absence of large flavor changing neutral currents it was shown that the Yukawa couplings are completely fixed. For instance for the lepton sector we get the Yukawa couplings

$$\mathcal{L}_{\text{Yuk}} = -\sqrt{2} \frac{m_\tau}{v} \left\{ \bar{\tau}_R \varphi_1^\dagger \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L - \bar{\mu}_R \varphi_2^\dagger \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \right\} + h.c. \quad (10)$$

In the unitary gauge electroweak symmetry breaking gives

$$\varphi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_0 + \rho' \end{pmatrix}, \quad \varphi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h' + i h'') \end{pmatrix} \quad (11)$$

with the standard vacuum-expectation value $v_0 \approx 246$ GeV. The physical Higgs-boson fields are ρ' , h' , h'' , and H^\pm .

Let us briefly summarize the essential properties of the MCPM:

- There are 5 physical Higgs particles, two CP even ones ρ' , h' , one CP odd one h'' , and a charged Higgs-boson pair H^\pm .
- The ρ' boson couples exclusively to the third (τ, t, b) family, ρ' behaves like the SM Higgs boson.
- The Higgs bosons h' , h'' , H^\pm couple exclusively to the second (μ, c, s) family with strengths proportional to the masses of the third generation fermions.
- The first (e, u, d) family is uncoupled to the Higgs bosons.

For further details we refer to [11].

2. PREDICTIONS FOR HADRON COLLIDERS

Since the Yukawa couplings of the h' , h'' , H^\pm Higgs bosons to the second fermion family are proportional to the third-fermion-family masses we have large cross sections for Drell–Yan type Higgs-boson production. For the same reason we have large decay rates of these Higgs bosons to the second generation fermions. In figure 1 we show the diagrams for these production and decay reactions in pp collisions.

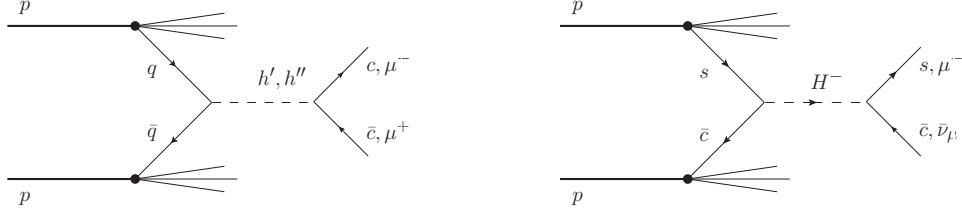


FIG. 1: Feynman diagrams for the Drell–Yan type Higgs-boson production and decay reactions which are enhanced in the MCPM ($q = c, s$).

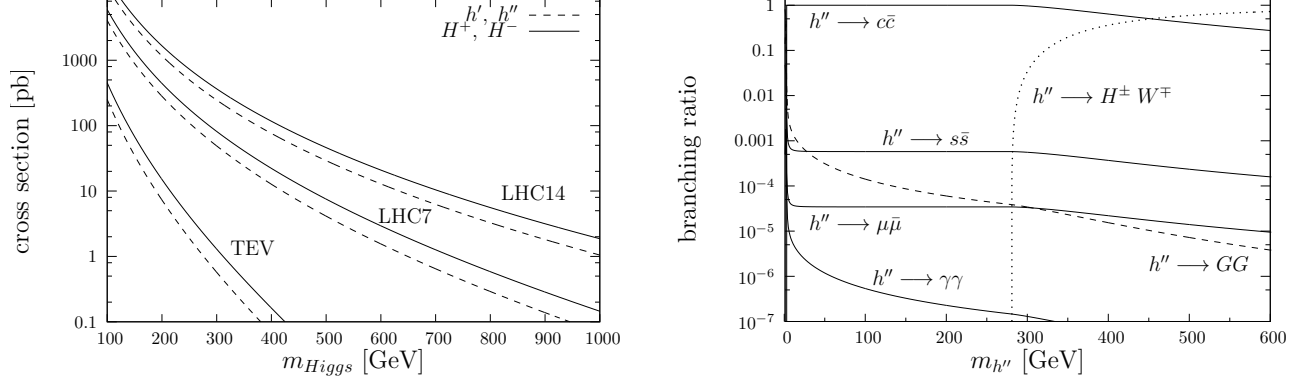


FIG. 2: left: total cross section of Drell–Yan type Higgs boson production at TEVATRON and LHC. right: branching ratios of the CP odd h'' Higgs boson, where a mass of $m_{H^\pm} = 200$ GeV is assumed.

In [12] the cross sections were computed for Drell–Yan Higgs-boson production at the TEVATRON and the LHC for center-of-mass energies of 1.96 TeV and 14 TeV, respectively. In [13] radiative effects were considered. Here we add the cross sections for a center-of-mass energy of 7 TeV at LHC, which is currently available. The corresponding total cross sections for the Drell–Yan production of the h' , h'' , H^\pm bosons are shown in figure 2. In this figure we also recall the branching ratios of the h'' boson decays. As an example consider Higgs-boson masses h' , h'' , H^\pm of 200 GeV where we get very large total production cross sections, around 850 pb, for LHC7. These Higgs bosons decay mainly into light c and s quarks. However, tagging of c and s -quarks in the detectors is at least challenging. Channels involving muons should be more easily accessible experimentally. With the branching ratio of 3×10^{-5} into μ -pairs, we predict about 25 μ events from a 200 GeV h' (h'') at LHC7 for 1 fb^{-1} integrated luminosity. For further details of the calculations we refer to [11–13].

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